Chapter 2

Polarized Proton Injector

To meet the required bunch intensity of 2×10^{11} protons per bunch in RHIC, the AGS as the polarized proton injector will need to reach a bunch intensity of about 4×10^{11} to allow for some losses during the transfer to RHIC for acceleration. Although it would be possible to use the existing polarized proton source[11] by accumulating up to twenty source pulses in the Booster, a new optically pumped polarized ion source (OPPIS) will be installed. The new polarized H^- source will produce $500\mu A$ in a single $300\mu s$ pulse, which corresponds to 9×10^{11} polarized H^-. This is sufficient intensity to eliminate the need for the accumulation in the Booster. The polarized H^- ions are accelerated to 200 MeV with an RFQ and the 200 MHz LINAC with an efficiency of about 50%. The pulse of H^- ions is strip-injected and captured into a single bunch in the AGS Booster. The bunch in the Booster will then contain about $N_B = 4 \times 10^{11}$ polarized protons with a normalized emittance of about $\epsilon_N = 10\pi$ mm-mrad. The single bunch of polarized protons is accelerated in the Booster to 1.5 GeV kinetic energy and then transferred to the AGS, where it is accelerated to 25 GeV. Fig. 2.1 shows the components of the AGS complex used for polarized proton acceleration.

2.1   Polarized Ion Source

The new RHIC optically pumped polarized H$^-$ source (OPPIS) is being constructed from the KEK OPPIS source, which has been transferred to TRIUMF for upgrade. The goal of the upgrade is to provide a DC beam of 1.5 mA H$^-$ with a pulsed polarization of 80% in 100 μs pulses at a repetition rate of 7.5 Hz. The polarized injector for RHIC must produce at least 0.5 mA H$^-$ ion current with 80% polarization during the 300 μs pulse, within a normalized emittance of 2π mm mrad. This is an ideal application for the ECR-type OPPIS. Pulsed lasers can be used to optically pump the rubidium vapor.

The first ECR-type OPPIS was constructed at KEK[12]. Polarized beam is not presently required at KEK, and so the source is at present being upgraded at TRIUMF to meet the RHIC requirements. It will be delivered to BNL in the first half of 1999, and design of the matching optics between the source and the RFQ has begun. Table 2.1 compares the RHIC requirements with what was previously demonstrated

Polarized Proton Experiments in the AGS with a Partial Siberian Snake (E880)

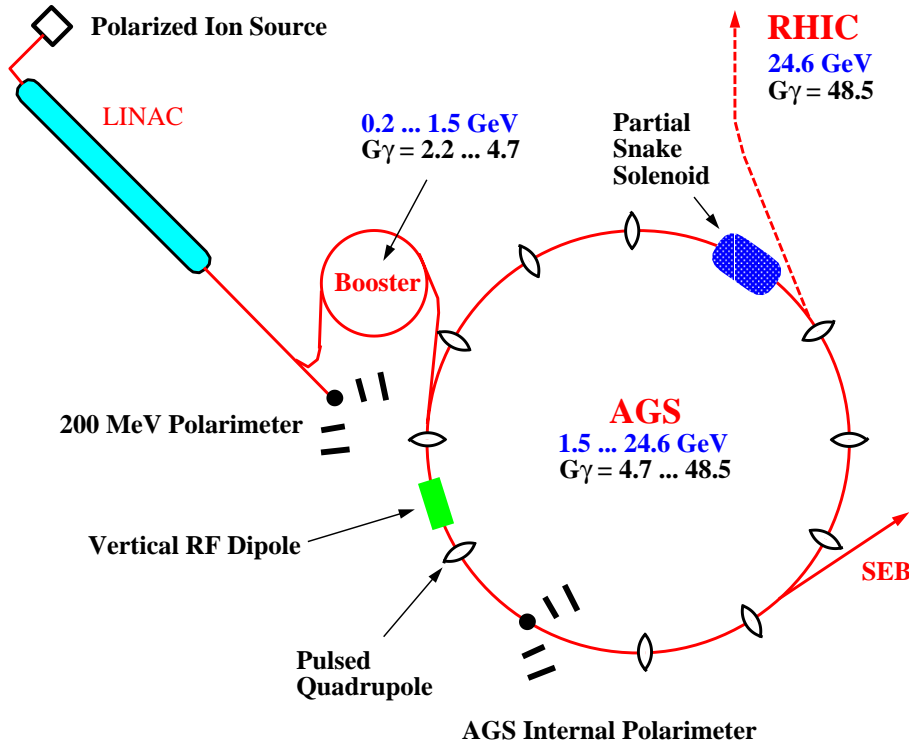## (ANL,BNL,INDIANA,TRIUMF,KEK,RIKEN,IHEP)

Figure 2.1: Schematic of the AGS complex for polarized proton acceleration.

on the TRIUMF OPPIS, and with the estimated KEK OPPIS parameters. (The KEK source was last operated for polarized D^- production[13]). The table shows that the existing TRIUMF design meets the RHIC requirements if 300 μs pulses are extracted, even with CW laser pumping. However, 100 μs pulse durations with peak currents of 1.5 mA would be preferred, since that would improve injection efficiency. The preference for the higher current, combined with the much lower cost of pulsed lasers relative to CW lasers, dictates the use of pulsed optical pumping. In previous tests at TRIUMF, near 100% Rb polarization was measured in a 2 cm diameter Rb cell having a vapor thickness of 1×10^{14} atoms cm^{-2} and a length of 30 cm, using a pulsed Ti:sapphire laser[14].

The KEK OPPIS as delivered to TRIUMF used a pulsed 18 GHz ECR proton source and CW laser pumping. At TRIUMF the KEK OPPIS is being optimized using a DC 28 GHz ECR proton source.

	KEK	TRIUMF	RHIC
Current (mA)	0.1	0.5	$0.5 - 1.5$
Pulse duration (μs)	100	DC	$100 - 300$
Charge/pulse (mA μs)	10	150 (in 300 μs)	≥ 150
Polarization (%)	75	85	≥ 80
Normalized emittance (mm mrad)	2π	2π	$\leq 2\pi$
Repetition rate (Hz)	25	DC	7.5

Table 2.1: RHIC OPPIS parameters and comparison with KEK and TRIUMF designs.

Preliminary results give 520 μA of H$^-$ DC current, using a 121-aperture extraction electrode with an overall diameter of 13 mm. This already satisfies the minimum RHIC beam current requirements, and a 199-aperture system will do proportionally better.

A new Na-jet negative-ionizer target is being developed, which has some advantages over the original canal and condensation chambers arrangement. A jet target can be shorter and the beam apertures larger, since Na vapor is more effectively confined. The condensed Na is recycled. Large apertures reduce secondary electron emission caused by the intense polarized atomic hydrogen beam striking the cell, and therefore may allow biasing the Na cell up to 32 kV. If so, a 35 keV beam from the source will be injected into an RFQ, without requiring that the whole source be placed on a high voltage platform.

The flashlamp-pumped pulsed Ti:sapphire laser produces pulse durations of 80 μs (FWHM) at a repetition rate of 1 Hz, using a simple power supply. The laser cavity is tuned with a 2-plate birefringent filter and a 0.5 mm thick etalon, producing a laser bandwidth of less than 20 GHz. The peak power density is more than 33 W/cm^2 over the 3 GHz Doppler broadened absorption width of Rb, for a 2 cm diameter laser beam. Previous results have shown that 14 W/cm^2 is enough to produce nearly 100% Rb polarization in a similar target[15]. Future development will concentrate on extending the pulse duration and repetition rate of the laser, mainly by increasing the capacitance of the power supply. Longer pulses may require the use of a different laser crystal, or two consecutive pulses.

2.2   Acceleration in the Booster and AGS

During acceleration, the polarization may be lost when the spin precession frequency passes through a depolarizing resonance. These resonances occur when the number of spin precession rotations per revolution $G\gamma$ (G=1.793 is the anomalous magnetic moment of the proton, $\gamma = \frac{E}{m}$) is equal to an integer (imperfection resonances) or equal to $kP \pm \nu_y$ (intrinsic resonances). Here P=12 is the superperiodicity of the AGS, $\nu_y \approx$ 8.8 is the vertical betatron tune and k is an integer. The depolarization is caused by the small horizontal magnetic fields present in all circular accelerators which, at the resonance condition, act coherently to move the spin away from the stable vertical direction. Imperfection resonances are due to the horizontal fields

caused by the vertical closed orbit errors and intrinsic resonances are caused by the horizontal focusing fields which are sampled due to the vertical betatron motion. The two weak resonances in the Booster ($G\gamma = 3$ and $G\gamma = 4$) are easily corrected by a harmonic correction of the closed orbit, since there are only two of them. Traditionally, the depolarizing resonances in the AGS were corrected by the tedious harmonic correction method for the imperfection resonances and by a tune jump method for the intrinsic resonances[16].

Three polarized beam test runs of experiment E-880 at the AGS have recently demonstrated the feasibility of polarized proton acceleration using a 5% partial Siberian Snake[17]. During the first run[18] in April 1994 it was shown that a 5% Snake is sufficient to avoid depolarization due to the imperfection resonances without using the harmonic correction method. The upper part of Fig. 2.2 shows the evolution of the beam polarization as the beam energy and therefore $G\gamma$ is increased. As predicted the polarization reverses sign whenever $G\gamma$ is equal to an integer. The lower part of Fig. 2.2 shows that no polarization was lost at the imperfection resonances. The only polarization loss occurred at the location of the intrinsic resonances for which the pulsed quadrupoles are required for the tune jump method. During the first run the pulsed quadrupoles were not available. Although some depolarization at intrinsic resonances are expected, the level of the depolarization does not agree with a simple model calculation. A spin tracking study was then performed and it showed that there is another resonance adjacent to the intrinsic resonance which causes further depolarization. Since the solenoidal 5% partial snake introduces considerable linear coupling between the two transverse betatron motions, the vertical betatron motion has a component with the horizontal betatron frequency. As a consequence, the beam will see an additional resonance, the so-called coupling resonance.

During the second run of E-880 in December 1994 it was shown that it is possible to use the tune jump method in the presence of the partial Snake. A new record energy for accelerated polarized beam of 25 GeV was reached with about 12% beam polarization left. Again no polarization was lost due to the imperfection resonances and depolarization from most intrinsic resonances was avoided with the tune jump quadrupoles. However, as can be seen from Fig. 2.3, which shows the achieved polarization as a function of beam energy, significant amount of polarization was lost at $G\gamma = 0 + \nu_y, 12 + \nu_y$ and $G\gamma = 36 + \nu_y$. The first two of these three resonances were successfully crossed previously and it is believed that the losses are partially due to the coupling resonances. The tune jump method changes the vertical betatron tune within less than one revolution to effectively make the resonance crossing speed very fast. However, the coupling resonance is still crossed at the normal crossing speed and can cause polarization loss. The strength of the tune jump quadrupoles is not sufficient to jump the third resonance. We attempted to induce spin flip at this resonance but were only partially successful. This is again due to the coupling resonance and the observed large momentum spread at this high energy. Table 2.2 summarizes the polarized proton beam parameters achieved in the AGS and also the requirements for RHIC.

A novel energy-jump method was used to cross the coupling resonance in the third run of E-880 and
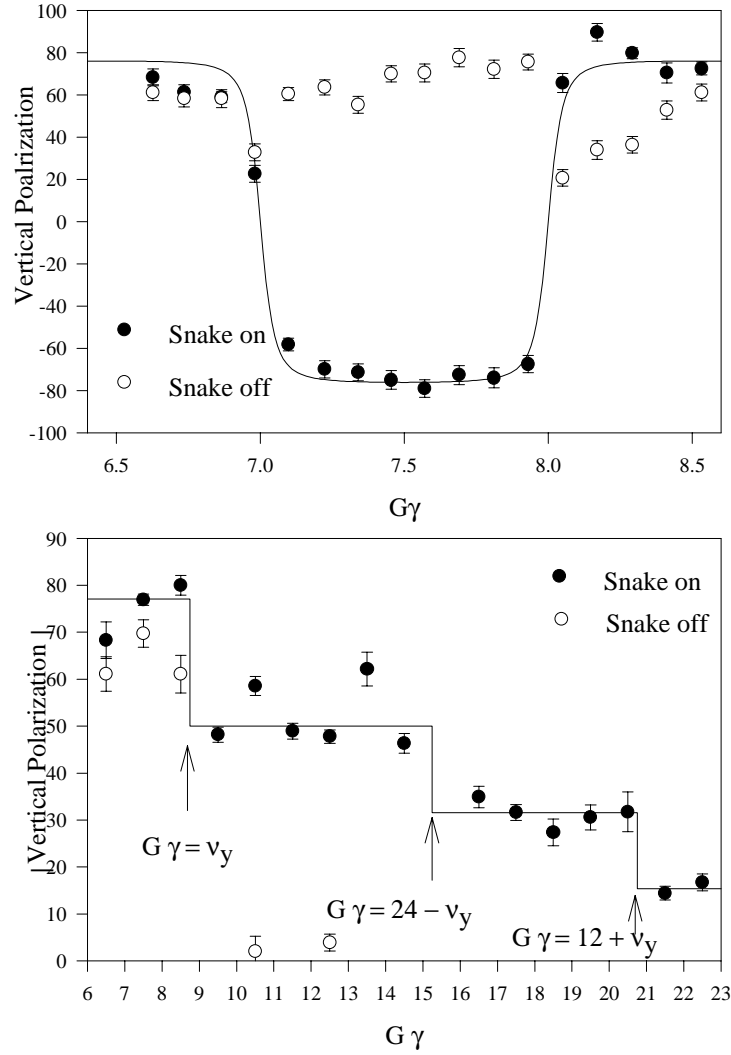
Figure 2.2: The upper figure shows the measured vertical polarization as a function of spin tune $G\gamma$ for a 10% Snake (solid dots) and without the Snake (open circles). Note that partial depolarization at $G\gamma = 8$ is avoided by using the 10% Snake. The lower figure shows the absolute value of the vertical polarization at $G\gamma = n + \frac{1}{2}$ up to $G\gamma = 22.5$ (solid dots). Note that partial depolarization only occurs due to the intrinsic resonances.

the results are summarized in Fig. 2.4. The energy-jump was accomplished by rapidly changing the beam circumference by 88 mm using the powerful AGS rf system. Because of the large momentum spread of the beam indicated as a hashed band in the lower part of Fig. 2.4, not all the beam particles are crossing the resonance during the jump unless the jump timing is carefully adjusted. From the beam momentum distribution, the ratio of the final to the initial polarization as a function of jump timing T_{jump} can be
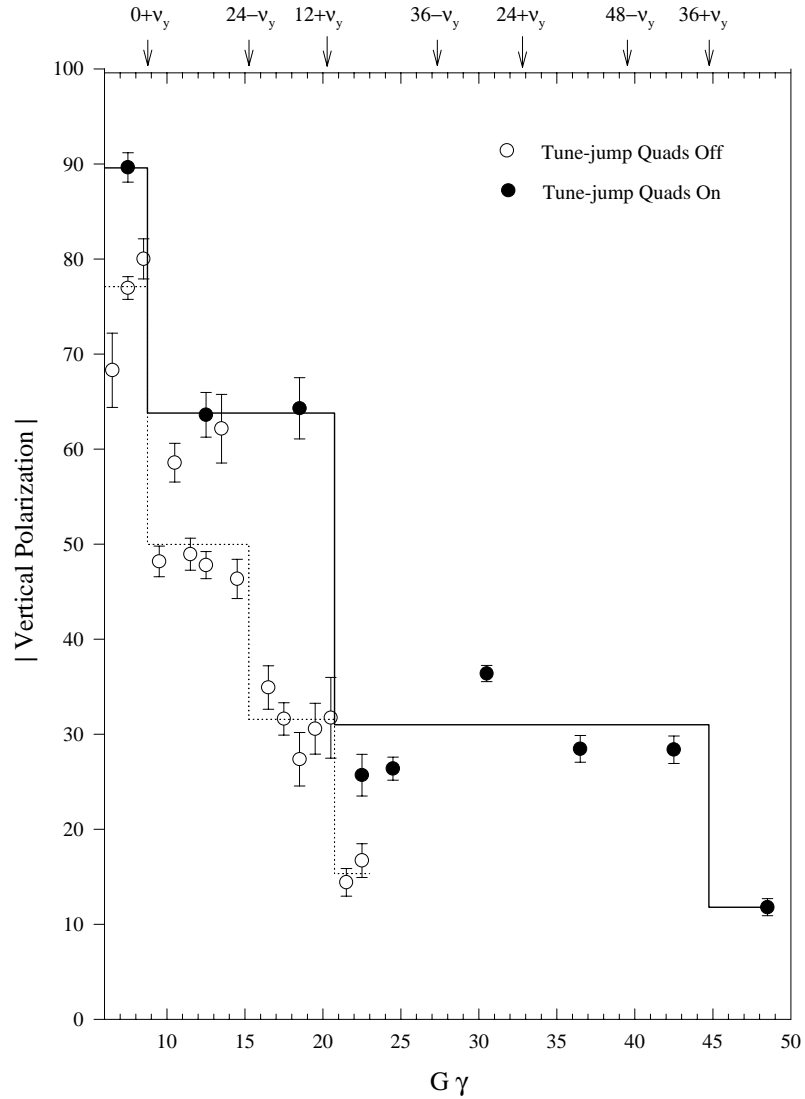
Figure 2.3: The absolute value of the vertical polarization is shown as a function of energy for the April 1994 run (open circles) and the December 1994 run (solid dots). Note that during the December run most intrinsic resonances were successfully crossed with significant depolarization only at the intrinsic resonances $G\gamma = 0 + \nu_y, 12 + \nu_y$ and $36 + \nu_y$.

	Intensity	Polarization	Emittance	Momentum
1988	1.8×10^{10}	65%		up to 13.3 GeV/c
		42%		up to 21.7 GeV/c
1994	0.5×10^{10}	64%	30π mm mrad	up to 10.7 GeV/c
		31%	30π mm mrad	up to 23.3 GeV/c
		12%	30π mm mrad	up to 25.4 GeV/c
RHIC	$2 - 4 \times 10^{11}$	$70 - 80\%$	$10 - 20\pi$ mm mrad	up to 25.4 GeV/c

Table 2.2: AGS polarized beam parameters. The 1988 data reflects the result of the many year effort to accelerate polarized beam in the AGS using pulsed quadrupoles and numerous correction dipoles. The 1994 date comes from the first two test runs of E-880 testing the Partial Siberian Snake in the AGS. The RHIC data shows the required beam parameters for the RHIC spin program.

predicted and is shown as the solid line in the top half of Fig. 2.4. It shows good agreement with the data. It clearly demonstrates that the novel energy-jump method can successfully overcome coupling resonances and weak intrinsic resonances.

In July and November 1997 a novel scheme of overcoming strong intrinsic resonances using a radiofrequency dipole magnet was successfully tested[19]. Full spin flip can be achieved with a strong artificial rf spin resonance excited by an rf dipole at a modulation tune ν_m. If we choose the rf spin resonance location $K_{rf} = n \pm \nu_m$ near the intrinsic spin resonance, the spin motion will be dominated by the rf resonance and the spin near the intrinsic resonance will adiabatically follow the spin closed orbit of the rf spin resonance. With the rf dipole, a new dominant resonance near the intrinsic resonance is introduced to flip the spin, instead of enhancing the intrinsic resonance which also enhanced the coupling resonance strength as has been proposed earlier[20]. Fig. 2.5 shows the new record proton beam polarization achieved during the last E-880 run. The rf dipole was used to completely flip the spin at the four strong intrinsic resonances $0 + \nu_y$, $12 + \nu_y$, $36 - \nu_y$, and $36 + \nu_y$. The lower curve shown going through the data points was obtained from a spin tracking calculation simulating the experimental conditions. Most of the residual polarization loss is caused by the coupling resonances. A new AGS partial Snake using a helical dipole magnet would eliminate all coupling resonances[21]. Spin tracking simulations of this condition are depicted by the upper curve in Fig. 2.5. The depolarization from the two weak intrinsic resonances $24 + \nu_y$ and $48 - \nu_y$ will be avoided using the energy jump method described above.

At 25 GeV, the polarized protons are transferred to RHIC. At this energy the transfer line between the AGS and RHIC is spin transparent[22]. If the last resonance, $G\gamma = 36 + \nu_y$, cannot be crossed without significant polarization loss it is possible to transfer the polarized protons to RHIC before crossing this resonance in the AGS at an energy of 22.4 GeV ($\gamma \approx 25$). This is discussed in the following chapter.

We estimate that the overall efficiency of the acceleration and beam transfer is better than 50%, giving 2×10^{11} protons per bunch. With proper care the normalized emittance of the bunch is expected to be much less than 20π mm-mrad. During the last E-880 run the vertical beam emittance was tuned to less than 10π mm-mrad. We repeat the process until all 120 bunches of each ring are filled. Since each bunch
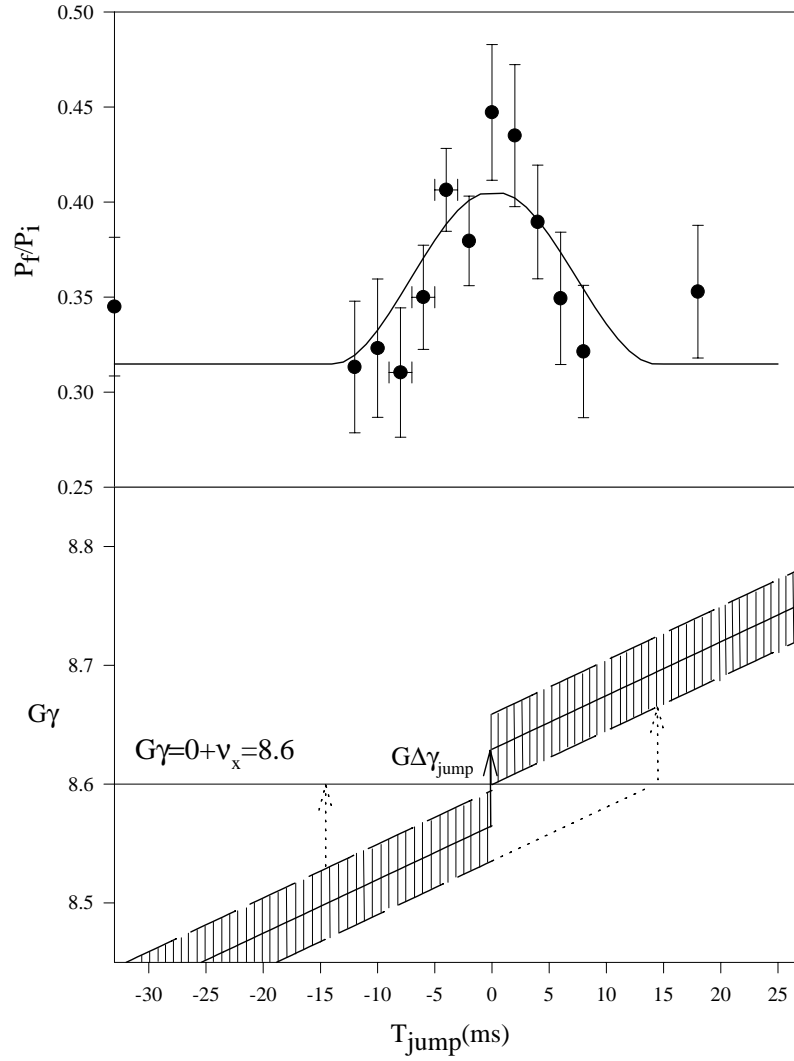
Figure 2.4: Energy jump data and schematics. In the top half, solid points are the experiment data, the solid line is the predicted curve. Bottom half shows the energy jump scheme.
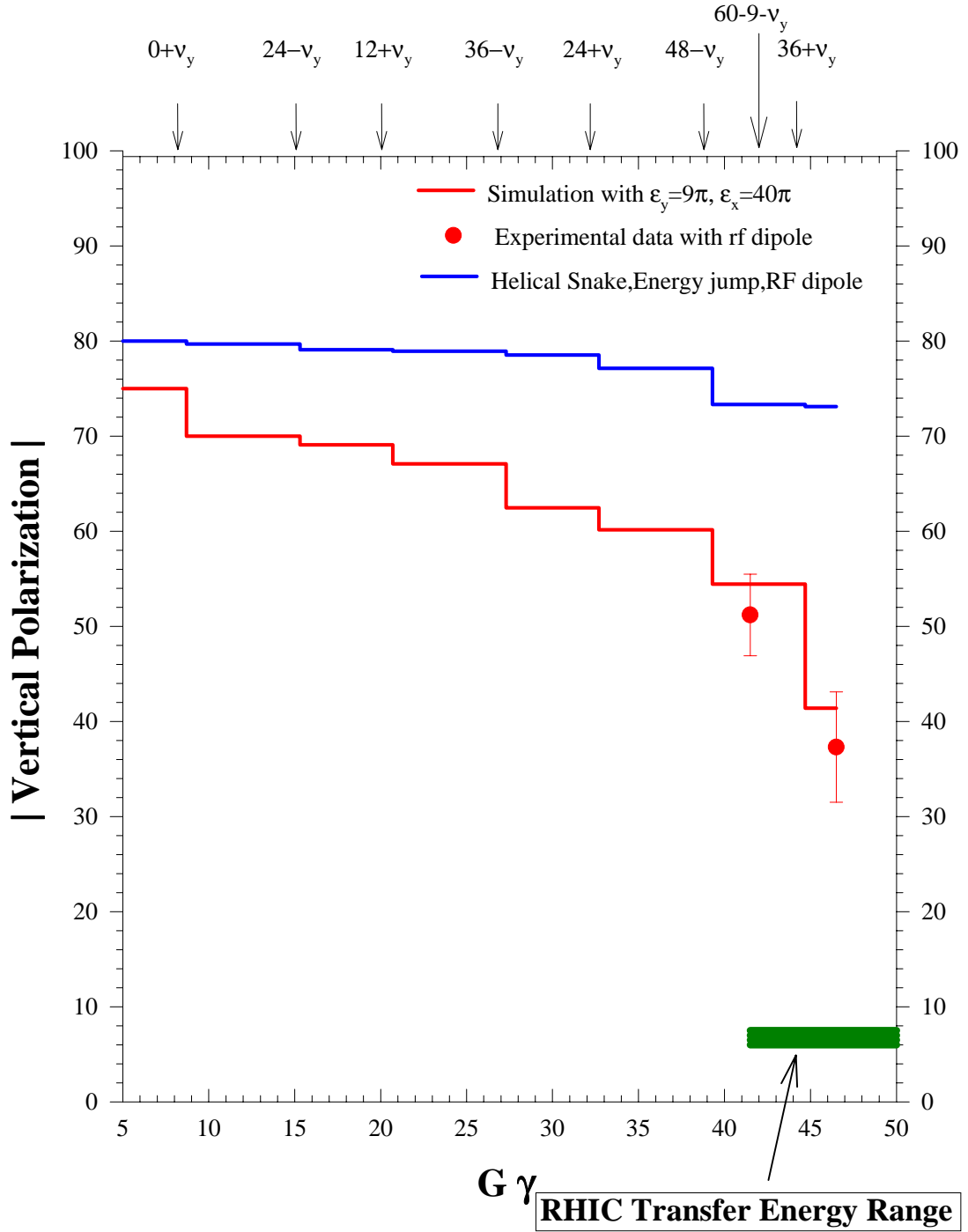
Figure 2.5: Vertical polarization versus $G\gamma$ measured during the November 1997 run of E-880. The lower curve is the result of a spin tracking calculation for the experimental conditions. The upper curve simulates the use of a helical partial Snake in the AGS.

is accelerated independently, we have the option of preparing the polarization direction of each bunch independently. Filling both RHIC rings with 120 bunches each and acceleration to full energy will only take about 10 minutes which is short compared to the expected lifetime of the stored polarized proton beams in RHIC of many hours.